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Optimisation of Air Source Heat Pumps in Residential Retrofits

Seamus Hoyne
Limerick Institute of Technology, seamus.hoyne@lit.ie

Padraic O'Reilly
Limerick Institute of Technology, padraic.oreilly@lit.ie

Michael O'Shea
Limerick Institute of Technology, michealp.oshea@lit.ie

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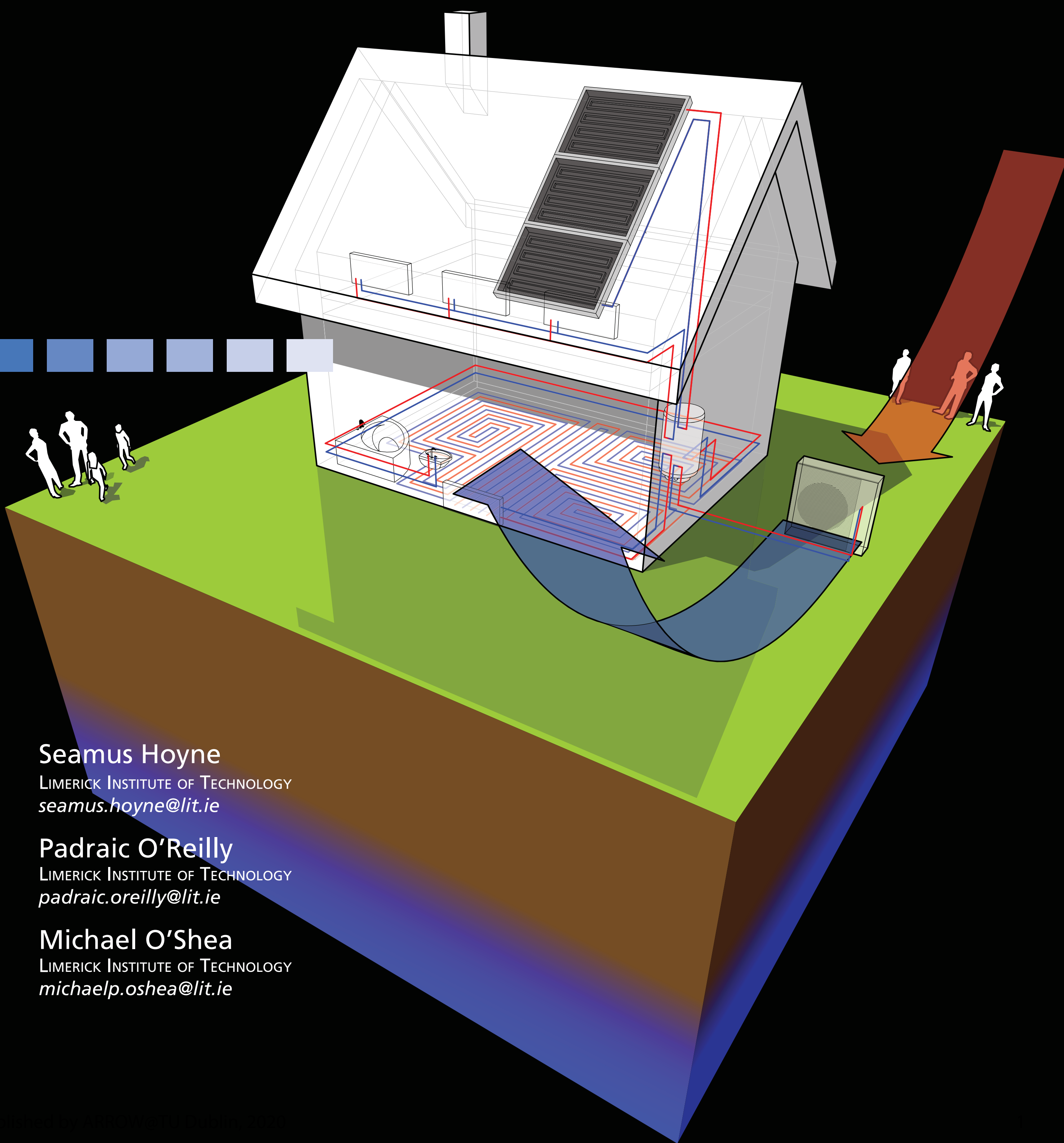

Seamus Hoyne
Limerick Institute of Technology
seamus.hoyne@lit.ie

Padraic O'Reilly
Limerick Institute of Technology
padraic.oreilly@lit.ie

Michael O'Shea
Limerick Institute of Technology
michaelp.oshea@lit.ie

Abstract

Correctly applied air source heat pumps (ASHPs) are a proven technology that can reliably and effectively replace fossil fuel heating systems and achieve targeted heating-related CO_2 reductions. However, poor-quality system design, installation or commissioning can lead to higher than expected running costs and poorly-performing heating systems, thus resulting in lower than expected CO_2 savings.

The retrofit ASHP systems studied in this research in residential retrofits in Ireland had significant engineering input at design stage, and comprehensive oversight during the installation and commissioning stages by the engineering team. Following analysis, most of the systems performed in line with, or exceeded, predictions but further opportunities for optimisation were identified. The research highlights the need for increased focus and resources to be applied by commissioning engineers to ensure that all ASHP installations are successful, a point that is especially critical in the context of the Irish Climate Action Plan targets of 500,000 retrofitted homes and the installation of 400,000 retrofit heat pumps by 2030 (Government of Ireland, 2019).

This paper presents recommendations on how the ASHP installation process can deliver systems that operate to their full potential in terms of energy efficiency and CO_2 reductions.

Keywords

Air source heat pump, retrofit, compressor cycle, defrost, commissioning, handover.

Abbreviations

ASHP: Air source heat pumps; CO_2:Carbon Dioxide; UFH: Underfloor heating; SH20: Superhome 2.0; LIT: Limerick Institute of Technology; TEA: Tipperary Energy Agency; KPIs: Key performance indicators; COP: Coefficient of Performance; SPF: Seasonal Performance Factor; CC: Compressor cycling; SH2.0_HS1: Superhomes 2.0 heating season 1; SH2.0_HS2: Superhomes 2.0 heating season 2; WCC: Weather compensation curve; T_{out}: Outside air temperature, °C; T_{sf}: Set flow temperature; T_f: Flow temperature; RH:Relative Humidity.

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1. Introduction

Superhomes is an approach to the retrofitting of residential buildings that has been pioneered by the Tipperary Energy Agency CLG (TEA … www.tippenergy.ie). Superhomes has completed 311 retrofits since 2015 and the Limerick Institute of Technology (LIT) has collaborated with TEA to research various aspects of the deep retrofit process, including the Superhomes 2.0 (SH2.0) project(LIT, 2019) which had as its main focus the optimisation of ASHPs in deep retrofit.

ASHPs are electrically powered renewable heating devices installed as heat generators in renewable heating systems. Heat pumps harness low temperature ambient energy from outside air, upgrading its temperature as it passes through the refrigeration process before transferring the upgraded heat into the water-based heating system in the dwelling. Space heat is provided through low-temperature emitters such as underfloor heating or correctly-sized radiators, and domestic hot water is produced in specially-designed storage cylinders. Typically, for every 3.5 units of heat energy supplied to the house, 2.5 units come from the ambient air and can be considered renewable energy. The remaining one unit of heat energy is obtained from the mechanical energy of the compressor added to the flow of energy through the heat pump. No fossil fuels are burnt on site and if homeowners purchase their power from a renewable supplier, they can consider their heating system to have zero CO_2 operating emissions.

Aside from the potential to reduce CO_2 emissions, lower running costs are another attraction for homeowners considering installing a heat pump … the annual running cost of an ASHP would typically be 53% that of an oil boiler, 40% of natural gas or 31% of an LPG boiler (SEAI, 2109). This benefit must, however, be balanced by the extra capital cost involved with a heat pump installation where a period of 5-7 years may be required for the annual savings to overtake the extra capital spend over and above that of a boiler installation.

Heat pumps have been installed commercially in Irish homes since around 2000. The design, installation and commissioning processes are more sophisticated that those traditionally employed for oil and gas-fired boilers due to the need for the overall system to operate at lower temperatures. Traditional fossil fuel boiler systems operate at flow temperatures in the region of 75°C and buildings built prior to 2005 typically have higher heat losses due to poorer insulation standards, when compared to 2020 standards. For these buildings, fossil fuel boilers were generally sized with a heat output significantly more than the peak heat load of the house, thus enabling relatively quick heat-up times. For heat pumps, equipment capacity should be much closer to peak space heating load, with design decisions to be made about whether to use back-up heaters to cater for peak demand (NSAI, 2007). This means that the sizing of domestic heating systems using heat pumps is a much more precise exercise than previously employed for fossil fuel boilers.

Heat pumps represented new technology for most homeowners in the SH2.0 project and, while it was evident that most did not engage with the system controls, preferring instead to depend on the installer to set the system up and not to make any adjustments themselves, all of the homeowners in the study group provided very positive feedback from their experience with the systems.

2. Background

SH2.0, funded by the International Energy Research Centre (LIT, 2019), ran from May 2017 to April 2019, collecting and analysing data from 20 ASHP systems designed and installed in domestic deep retrofit projects funded by the Sustainable Energy Authority of Ireland (SEAI). System design was advised by CIBSE guidelines (CIBSE, 2016) and IS EN standards (NSAI 2003, 2007, 2012). The design process involved carrying out room-by-room heat loss calculations to calculate an overall space-heating requirement and thereby select a heat pump with this heating capacity.

The nature of the space heating emission systems varied across the 20 houses – 12 were heated exclusively by radiators, in which case existing radiators were replaced by new radiators sized to cater for the peak heating load with flow temperatures of 48°C; eight houses had underfloor heating in the living areas of the house, with three of these being newly-installed during the retrofit process; while five re-used existing underfloor heating (UFH) systems. Of the eight houses with UFH systems, five had radiators while three had UFH in sleeping areas. Table 1 presents an overview of the 20 systems.

Space heating control was managed by time schedules and room temperature thermostats. Houses with radiators in both living and sleeping zones had one master thermostat for each zone. This was set to achieve comfort levels during specific time slots, outside of which the units controlled to an adjustable set-back temperature.

Superhome Reference	Total floor area (m^2)	BER	Heat Emitter Zone 1	Heat Emitter Zone 2	ASHP Capacity (kW)
SH001	167	A3	Radiators	Radiators	8.5
SH005	229	A2	Radiators	Radiators	11.2
SH006	191	B1	UFH and Radiators	Radiators	8.5
SH009	214	A3	UFH	Radiators	11.2
SH014	203	A3	UFH	UFH	11.2
SH016	296	A2	Radiators	Radiators	11.2
SH018	133	B1	Radiators and Aga	Radiators	7.5
SH020	303	A3	UF and Radiators	Radiators	16
SH031	143	A3	Radiators	Radiators	8.5
SH067	175	A3	UFH	Radiators	8.5
SH073	245	B2	UFH + 1 Radiator	Radiators	11.2
SH076	231	B1	Radiators	Radiators	8.5
SH086	201	A3	Radiators	Radiators	8.5
SH103	196	A3	Radiators	Radiators	8.5
SH123	215	A3	Radiators	Radiators	8.5
SH127	168	A3	Radiators	Radiators	8.5
SH139	227	A3	Radiators	Radiators	11.2
SH149	227	A3	Radiators	Radiators	8.5
SH202	148	B1	UFH	Radiators	8.5
SH212	129	B3	UFH	Radiators	8.5

Table 1: Overview of SH2.0 test sites.

3. Heat pump performance research methodology

The purpose of SH2.0 was to research optimisation of real-world residential energy retrofit installations that included ASHPs. To this end, LIT was furnished with data and access to the installations for the purposes of carrying out tests over a two-year period. Opportunities such as this to assess the energy performance of systems in real-world buildings are limited as evidenced by the lack of performance data on ASHPs when reviewing the literature. SH2.0 ASHP data was available at a minute-by-minute scale, thus allowing for detailed analysis of performance factors.

Data was collected in three ways – remote login to the manufacturer's platform, site visits to collect data on SD cards, and downloads provided from the manufacturers. Quality assurance measures were employed to ensure data quality was to the highest levels. These data sources enabled macro assessment of the performance of each ASHP in terms of Key Performance Indicators (KPIs) such as Coefficient of Performance (COP), average flow temperature and compressor cycles, as well as detailed analysis of operating events on a minute-by-minute basis. In some cases, KPIs were taken directly from the monitored data while specific algorithms were developed for the quantification of other metrics, e.g. compressor cycles (CC). Data was collected over two heating seasons (Oct 2017 to April 2018 and September 2018 to April 2019).

The initial phases of the research concentrated on data quality and dataset development for each dwelling/ASHP to enable ASHP performance to be compared to benchmarks from literature and to other systems in the study. Datasets were developed for the first heating season (SH2.0_HS1, Oct'17-Apr'18) and, based on the analysis of these datasets, areas for more detailed investigation were identified. Optimisation measures were devised and implemented for the next heating season (SH2.0_HS2). Table 2 presents a sample dataset.

The areas chosen for further investigation were:

1. Compressor cycling (CC) and flow temperature control;
2. Defrosting and the impact of heat pump sizing.

3.1 Compressor cycling and flow temperature control

EN15450 states: "In order to minimise cycling, it shall be assured that the heating capacity delivered by the heat pump is completely transferred to the heating system" and recommends a target maximum of three compressor starts per hour. High CC leads to:

- Reduction in COP and thus an increase in running costs;
- Burning out of electrical components;
- Reduction in the lifespan of the compressor.

The dataset for SH2.0_HS1 was assessed to determine the scale of CC occurring across the systems. Measures to optimise CC were identified and applied and further analysis conducted on SH2.0_HS2 data to determine the relevant impacts.

ASHP COP increases as the difference between the outside air temperature and flow temperature reduces. Thus, ASHP space heat-ing systems are classified as low temperature systems and typically use underfloor heating or radiators as room heat emitters. When working with heat pumps, underfloor heating systems are designed to deliver peak heat loads with flow temperatures in the range 30-35°C, while radiator systems are typically designed for peak flow temperatures in the range 45°C/55°C.

The ASHPs in the study all had the option of being controlled using weather compensation curves (WCC), where the target flow temperature is automatically adjusted in response to changing outside temperature.

Following SH2.0_HS1, amendments were made to WCC across dwellngs to determine the impact on AHSP performance, in particular on CC and COP. A case study is presented of one of these field trials.

3.2 Defrosting and the impact of heat pump sizing

At low outside temperatures (T_{out}) and high relative humidity (RH), ice starts to build up on the surfaces of the evaporator during AHSP operation. Eventually, this ice causes a reduction in heat transfer from the outside air to the refrigerant. The ASHP controller will detect this occurrence and initiate a de-frost cycle whereby the refrigeration system is reversed so that hot gas enters the evaporator, thus causing the ice to melt. The process typically lasts three to four minutes and involves energy consumption by the compressor as well as a temporary interruption of the ASHP's heat delivery to the house.

The main considerations for the operation of the ASHP system resulting from the defrost process are:

1. The energy required to complete the process with no resultant heat to the house;
2. The effect of reducing output on COP as the ice builds up;
3. Defrost interruptions preventing the unit from achieving target flow temperatures and the related impact of heat pump sizing.

Predicted annual performance could be overstated if points 1 and 2 are not taken into consideration. The impact of point 3 could lead to difficulties achieving target room temperatures during periods where defrosting is prevalent, especially where the heat pump is marginally undersized for the house space heating load. The systems in this survey did not employ electrical back-up heaters when operating in space heating mode. ASHP data was assessed to determine the frequency, scale and energy consumption associated with de-frost cycles and optimisation measured identified.

Superhomes 2.0 Datasets

Site	Month	Birr Degree Days	Average Outdoor T in Heating	Avg. Tf in Heating	Avg. ΔT in Heating	Avg. Heating Output (kW)	Heating Hours	Z1 SP Events[4]	Z2 SP Events	Total Cycles [1, 2]	Max Cycles /hr[3]	Z1+Z2 %	Z1 %	Z2 %	All Modes Consumed WH	Heating Consumed Wh	Heating CoP	Hot Water CoP	Total CoP (All modes)	Heating Consumed Wh / DD / m2	Unique Defrost events
SH005	Oct-17	141	10.9	35	3.8	4.9	232	2	1	166	4	33%	34%	33%	391,062	266,438	4.3	2.9	3.8	8	9
SH005	Nov-17	261	7.0	36	4.2	5.5	322	10	21	165	4	47%	29%	24%	728,833	481,348	3.7	2.2	3.2	8	67
SH005	Dec-17	313	5.9	36	3.9	5.1	488	47	43	476	5	75%	11%	14%	872,898	722,966	3.5	2.5	3.3	10	130
SH005	Jan-18	311	5.5	36	3.6	5.0	530	30	48	374	6	64%	28%	8%	940,543	779,860	3.4	2.6	3.2	11	143
SH005	Feb-18	339	3.8	37	3.9	5.7	466	34	40	172	4	57%	38%	5%	952,863	830,957	3.2	2.3	3.1	11	164
SH005	Mar-18	342	4.2	39	3.4	4.8	504	19	15	118	3	32%	67%	1%	975,689	836,346	2.9	2.3	2.8	11	181
SH005	Apr-18	212	7.8	35	3.4	4.7	322	8	16	163	3	45%	52%	3%	483,071	406,776	3.7	2.6	3.5	8	50
SH005	May-18	132	7.7	34	3.5	5.0	61	0	1	28	2	53%	46%	2%	80,482	78,770	3.9	2.4	3.9	3	9

Table 2: Sample of SH2.0 dataset.

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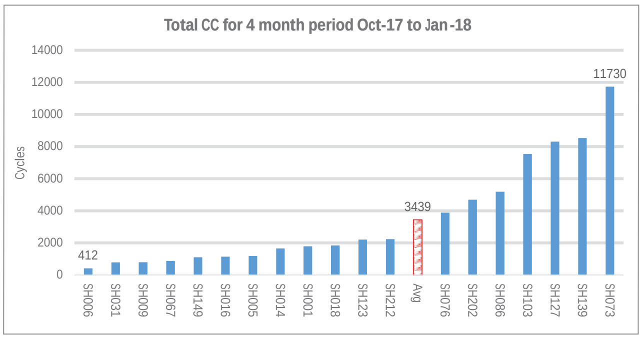

Figure 1: Compressor cycles.

4. Results and analysis

4.1 Compressor cycling

Figure 1 shows the total number of cycles for the four-month period of October 2017 to January 2018 for 19 of the 20 Superhomes. Applying the target of three starts per hour from EN14540 for nine hours of active heating per day yields a target of 3,240 CC for the four-month period. The average for the 19 houses shown above in Figure 1 was higher than this at 3,439 with seven houses exhibiting CC higher than this, significantly so in some cases.

On-site investigation of SH202 and SH073 found that the underfloor heating controls in these houses could create situations where the heat pump was required to provide heat to a small portion of the dwelling, thereby creating a mismatch between ASHP output and the heat emission capability of the system. The other above-average houses (SH076, SH086, SH103, SH127, SH139) had radiators in living and sleeping zones. For these systems, the focus of investigation was the impact of flow temperature on the effective operation of the heating system as a whole.

The operating patterns of the dwellings with high CC were reviewed by assessing ASHP performance under varying conditions. Figure 2 presents AHSP performance for SH139 where the outside temperature ranged from 9-13°C. The target switch-off room temperature for Zone 1 was 21.5°C, but over the 11 hours depicted on the graph, this target was never reached, despite the system being active for the entire period. This indicates that the set-flow (T_{sf}) temperature of the ASHP, and thus the heating system temperature, was too low for the conditions on that day. T_{sf} varied from 30-35°C in response to changes in outside temperature – actual flow temperature tracked set-flow temperature very closely, oscillating a few degrees above and below the target as the compressor switched on and off. Compressor switching is also evident from the fluctuations in consumed electrical energy.

Critically, examples such as this, where flow temperature was not high enough for the radiator system to heat the rooms to the set room temperature, were found in all radiator systems with high CC. WCCs were found to be set to deliver 48°C when outside temperature (T_{out}) was -3°C and 28°C/32°C when T_{out} was +15°C. This second setting was found to be too low for radiator systems, resulting in an insufficient temperature difference between the radiator and room temperatures, and leading to insufficient radiator heat output. In such scenarios, even when modulated to minimum output, the ASHP produced more heat than the radiators could emit and so, to avoid overshooting its target temperature, it was forced to switch off, switching back on again when the flow temperature had dropped below a re-start threshold. The problem was compounded by the fact that the situation could continue indefinitely as the ASHP would not switch off until the room target temperature was reached. This led to unnecessary energy consumption.

Homeowners provided anecdotal evidence to support this finding. During milder weather, they found that the heating system did not work as well as it did during colder weather, which is explained by the higher flow temperatures as T_{out} approaches -3°C.

4.2 Flow temperature control experiment

Figure 3 and Figure 4 (next page) show the results of tests carried out on SH086 to investigate the effect of adjusting the WCC on CC and COP. They present two 14-day periods where the Heating Degree Days (HDD) were very similar (approx. 155). For the range of T_{out} the graphs compare nominal heat pump output to the average actual heat output, nominal COP to actual COP, and the WCC target flow temperature to the actual average flow temperature.

The graphs present two WCC settings where there was an increase in target T_{flow} at T_{out} = 15°C from 28°C (Figure 3) to 45°C (Figure 4). In Figure 3 with the lower WCC, CC is significant, and the average output of the heat pump ranges from 5.5kW down to 1kW, with fall-off in heat output for T_{out} > 6°C. According to the manufacturer's datasheet, the minimum output possible for T_{out} between 6°C and 12°C for the flow temperature range presented is 3.68kW. The fact that average heat output is lower than this minimum in this region of the graph indicates extensive non-steady state compressor operation.

In Figure 4 with a higher WCC, CC is almost eliminated, and the actual average ASHP output is in keeping with the manufacturer's data indicating significant steady-state operation. This is further borne out

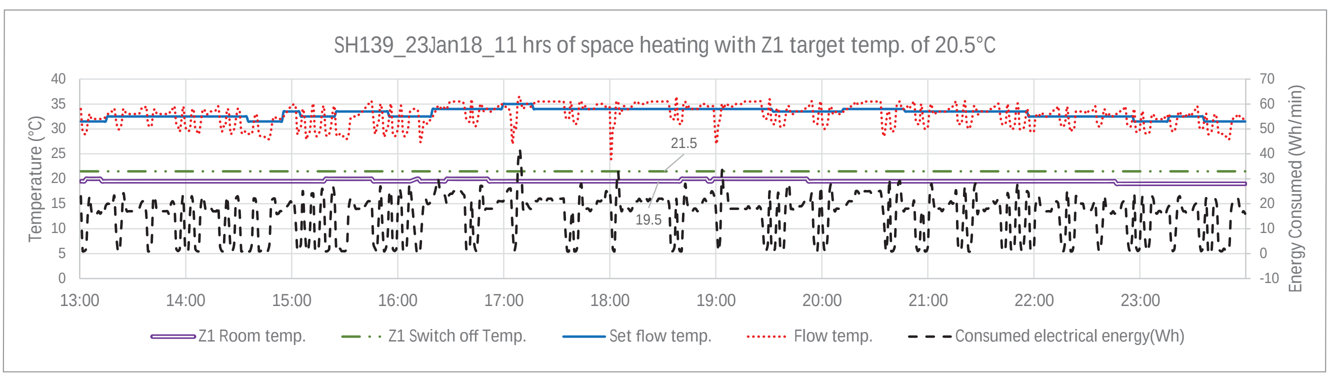

Figure 2: Space heating, flow temperature too low.

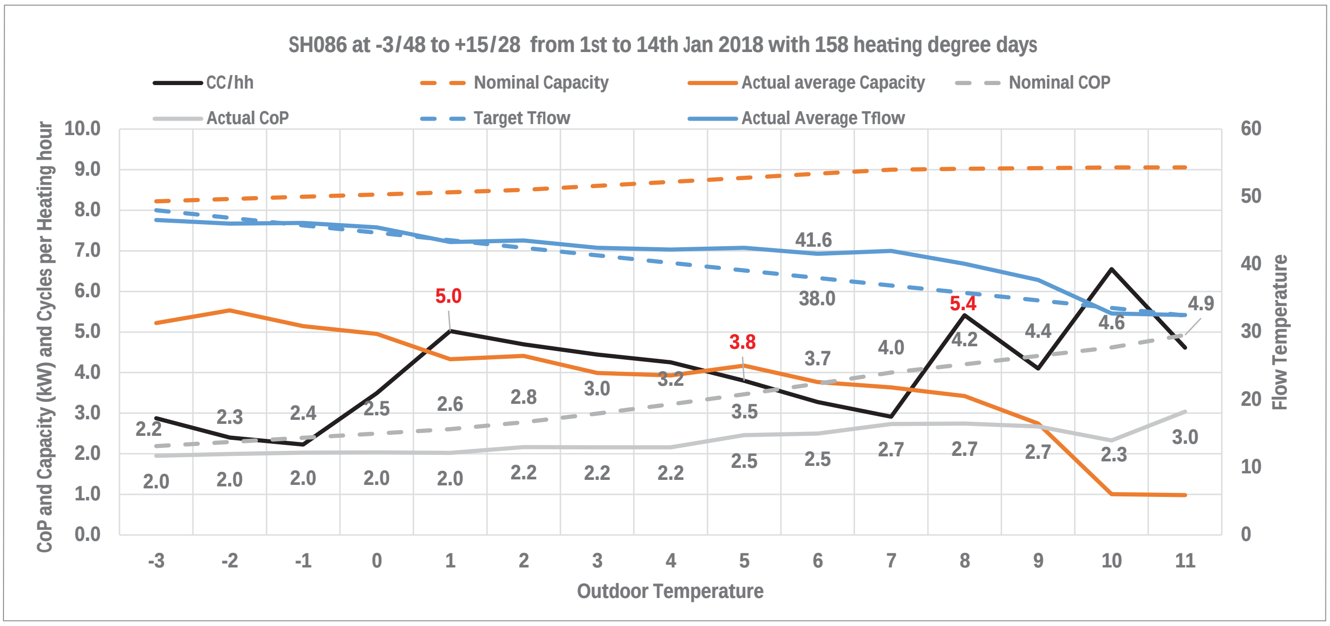

Figure 3: SH086 trial with low WCC setting for T_{out} = +15.

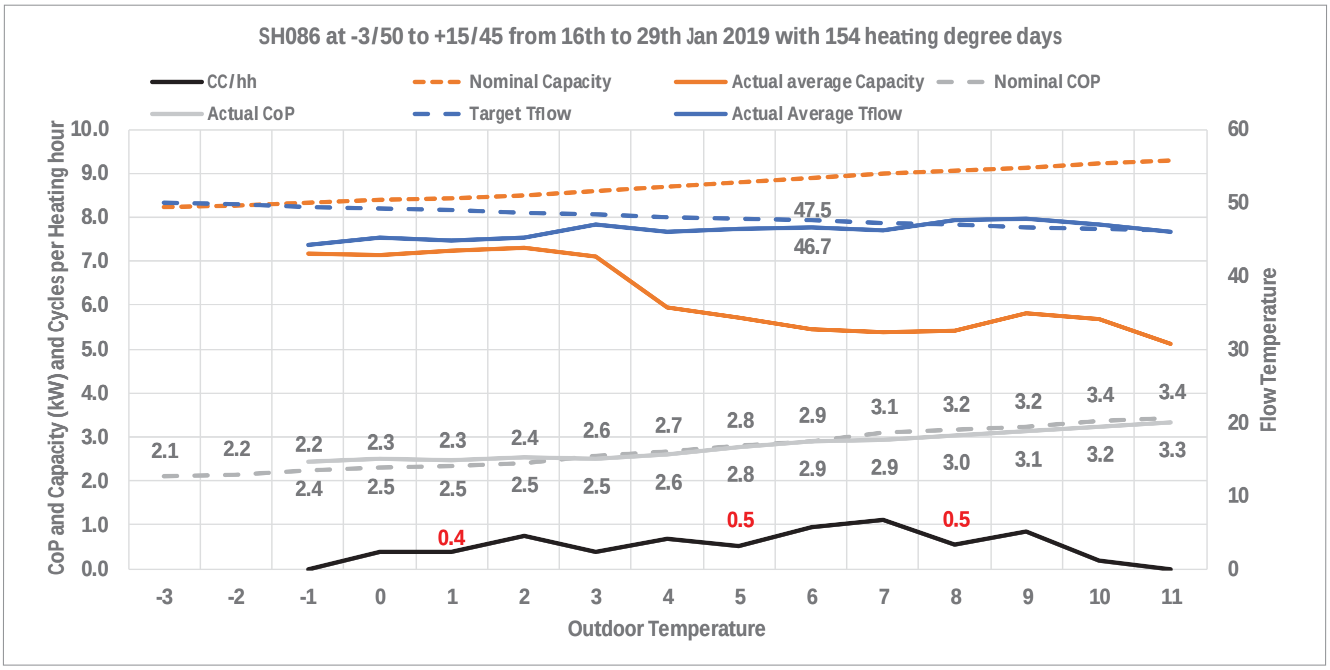

Figure 4: SH086 trial with high WCC setting for T_{out} = +15.

by the fact that the actual COP tracks the predicted COP very closely.

Where the heat pumps are directly coupled to radiator systems, higher target flow temperature allows the heat pump to operate for longer before having to switch off. The benefits arising from this are a more predictable COP, lower CC and the fact that the higher flow temperature will lead to a more responsive radiator system that is better able to satisfy room temperature target. In order to balance these benefits against the need for maximising COP, it is perhaps not necessary to increase the lower end of the WCC as far as 45°C. Correct radiator sizing and zoning to match radiator output to minimum ASHP output should enable systems to work efficiently with minimum flow temperature of 35°C for T_{out} = 15°C.

4.3 Defrost cycles

To assess the impact of the defrost cycle, ASHP data was analysed to determine the control process and activities of the ASHP components. Once the defrost cycle is initiated, the heat pump continues to operate in heating mode for approximately 90 seconds, after which time the fan switches off and the compressor continues to run at a low speed. Some seconds later, the reversing valve operates, thereby diverting hot gas to the evaporator. This process continues for approximately two minutes, after which the defrost signal disappears and the compressor switches off, signifying the end of the defrost period.

Table 3 (next page) presents the data for a defrost event for SH006 from the 8th November 2018 when T_{out} was 3°C. The controller flags

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Minute	Consumed electrical energy (Wh)	Delivered heat (Wh)	Cop	Defrost
1	51	144	2.82	0
2	53	123	2.32	0
3	54	125	2.31	0
4	54	120	2.22	0
5	54	112	2.07	2
6	16	48	3.00	2
7	8	0	0.00	2
8	9	0	0.00	2
9	5	0	0.00	2
10	1	0	0.00	0
11	7	0	0.00	0
12	35	88	2.51	0
13	42	83	1.98	0
14	44	92	2.09	0
15	44	111	2.52	0
16	51	121	2.37	0
17	52	127	2.44	0
18	52	128	2.46	0

Table 3: Sample defrost event.

the defrost event in minute 5 but it is not until minute 7 that it can be said that the unit stops delivering heat to the house. Between minutes 7 and 11, a total of 30Wh of electrical energy was consumed without any related heat output. From minute 12 onwards, heat is again delivered to the house. During SH2.0_HS1, SH006 experienced 1,362 defrost events consuming approximately 41kWh or 1% of total energy consumed for that period.

4.3.1 Energy penalty due to ice build-up

Figure 5 presents an example of the effect of evaporator ice build-up on the ASHP's heat output and consequently on COP for SH006. At minute one, the AHSP commences operating in heating mode having come out of a defrost cycle. The Evaporator is free of ice and so the operation from minutes 1 to 14 can be regarded as normal operation, where the ASHP goes through a start-up period, modulation and then a gradual increase in heat output to the point where output begins to level off. From minutes 14 to 31, due to ice build-up, heat output and thus COP gradually reduce while the electrical consumption remains steady at approximately 52Wh/minute. During this period, the COP falls from 3.52 to 2.82. Between minutes 31 and 33, the fall in output is severe with the COP dropping from 2.82 to 2.22. At this point, heat output drops to zero signifying the beginning of a defrost event. In this example, the total heat produced was 3,279Wh with an electrical input of 1,116Wh, a COP for the event of 2.94. Had there been no drop off in heat output, the total heat produced would have been 4,559, giving a COP of 4.08. The "lost" energy output from the ASHP was calculated to be 313Wh.

Applying this methodology to all the defrost events experienced by SH006 in SH2.0_HS1 indicated a total of 426kWh which was lost. This equates to 8.7% of the total energy consumed by the AHSP for that period. This loss in performance is in addition to the energy consumed during the defrost process.

4.3.2 Effect of defrost operations on ability to maintain house temperature

Figure 6 (next page) presents a 12-hour period of heat pump operation where T_{out} falls from 1˚C to -3˚C, thereby increasing the house's heat load. The graph of consumed energy shows that the heat pump was in operation for the full duration of the period, the only breaks in electrical consumption arising from periodic defrost events. Energy consumption rose from around 65Wh/min to in excess of 100 Wh/min for the period up to 2:00am due to a domestic hot water (DHW) event. As the night progressed and T_{out} fell to -3˚C, the level of

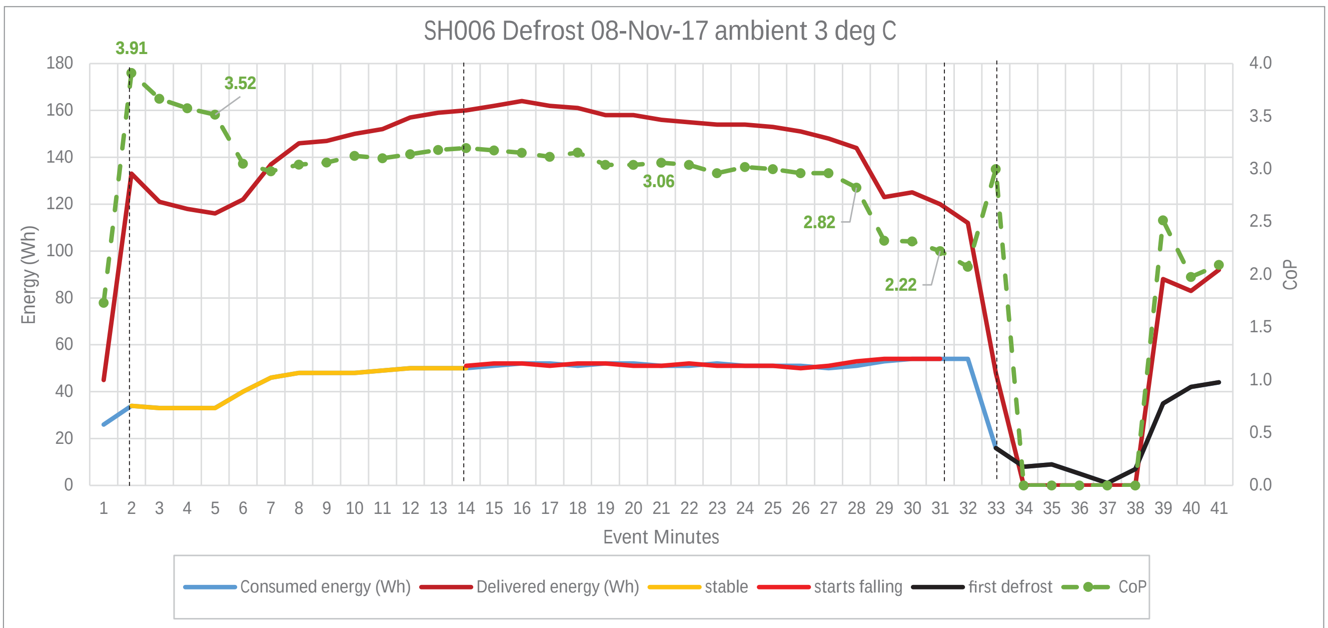

Figure 5: ASHP performance with ice build-up.

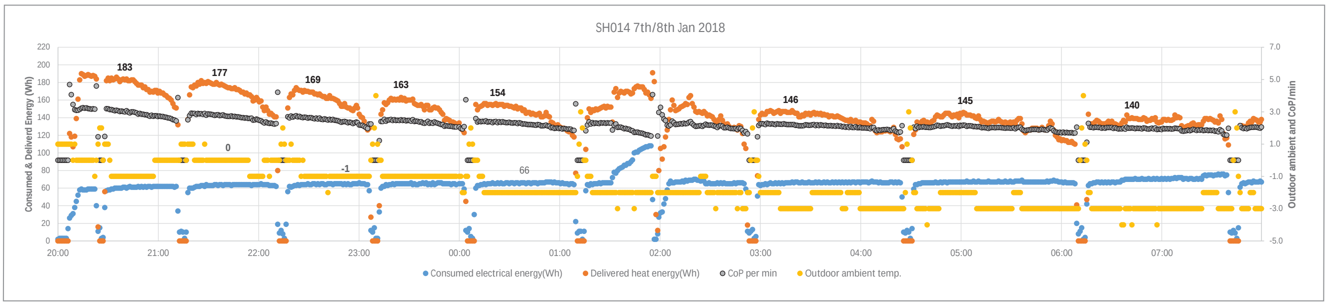

Figure 6: Heat pump sizing and defrost events.

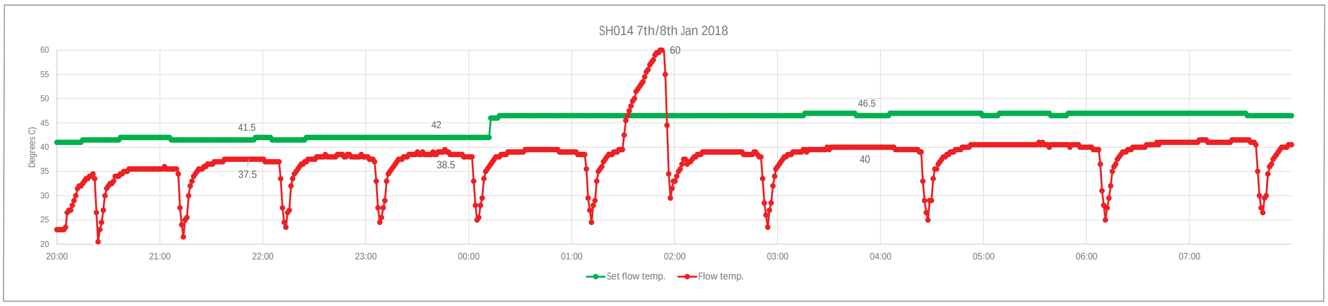

Figure 7: Not achieving flow temperature target.

Category	SH014	SH127
DEAP W/K	515	345
House Load (kW) at -3°C T_{out}, T_{int} = 20°C	11.85	7.94
Heat Pump capacity (kW) at -3°C T_{out} (Tf = 50°C)	11.03	8.22
Spare capacity (kW)	-0.82	0.28
Spare capacity %	-6.9%	3.5%
Zone 1: Minutes below internal target temperature	47,381	77
Zone 2: Minutes below internal target temperature	34,387	2,675

Table 4: Comparison of heat pump sizing.

energy consumption increased slightly while the heat output of the unit reduced, in line with a drop in T_{out}.

For the five cycles before 1:00am, each time the system re-started after a defrost event, heat output reached a peak before falling quickly to around 140 Wh/min with the peak achieved during consecutive cycles reducing from 185 to 155Wh/min. Later in the night when T_{out} was between -1˚C and -3˚C, the peak outputs achieved in each cycle were lower, but output degradation was also evident. Overall, the relatively consistent electrical consumption, together with reducing heat output, produced a reducing profile for COP.

Figure 7 shows the effect of the reduction in heat output on the ability of the heat pump to achieve its target flow temperature for the same period of operation as described in Figure 6. Each time T_f drops from high to low represents a defrost event. Excluding the DHW spike in the middle of the graph, actual flow temperature is constantly below T_{sf}. The increase in T_{sf} after midnight is caused by a reduction in T_{out} with a resulting increase in the differential between T_{sf} and T_{flow}. In this case, the ASHP was slightly undersized for the peak house load (see Table 4) and consequently the house internal temperatures were found to fall gradually during the night instead of being maintained at the living area target of 21˚C and sleeping area target of 18˚C. Undersized heat pumps will need to defrost frequently in low ambient temperatures, reducing the system's ability to reach and maintain set point (IHPA, 2018).

4.3.3 ASHP sizing example

Table 4 provides details of two of the SH2.0 systems in terms of maximum ASHP capacity, predicted maximum instantaneous house load as calculated by the Dwelling Energy Assessment Procedure (DEAP) tool, and the amount of time while in heating mode that the internal temperature was below target for each zone. The information presented includes all minutes during the heating season from October 2017 through to April 2018 when the ASHP was operating in space heating mode. The analysis demonstrated that the system, with a small % of spare capacity (SH127) i.e. slightly oversized, has significantly lower periods when the zone temperatures are below target when compared to the system which is slightly undersized (SH014).

5. Discussion and conclusions

The primary aim of the Superhomes 2.0 project was to collate data from 20 ASHPs in domestic retrofits and to measure their performance in terms of several key performance indicators. The data showed that while all systems performed well within expected performance and efficiency ranges, some opportunities for optimisation were identified.

All of the heat pumps in this study were of the variable capacity type (inverter) where the unit has the ability to adapt its heat output to match the house load. However, when the heat load available to the

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heat pump is less than its minimum capacity, the heat pump will cycle on and off between the minimum output and zero output leading to compressor cycling (CC). This was identified as having a negative effect on COP and on the life expectancy of the equipment.

The presence of cycling reduces the percentage of heat pump operating time spent in steady-state conditions which are the conditions that exist during heat pump output and COP tests in accredited laboratories. These steady-state COPs are used by national bodies when predicting national targets for energy consumption and CO_2 reductions achieved by ASHPs, so it is critical that all parties involved in the ASHP value chain are aware of the importance of avoiding CC.

In addition to ensuring a good match between heat pump and emission system outputs, optimal performance is achieved when interruptions to flow through the heat pump condenser, and thus CC, are minimised. This allows the ASHP to operate as closely as possible to the outputs and efficiencies in manufacturer's performance charts.

Interruptions can be mechanical such as the reduction in available heat load due to room-by-room zone valves in underfloor heating systems. This is also relevant to radiator systems using either thermostatic radiator valves or manifolds with electric actuators. These issues often originate from the practice of applying system designs that are appropriate for boilers but not appropriate for heat pumps. Buffer vessels are a solution to this problem in that they provide the heat pump with sufficient load to guarantee minimum run times that will allow for a maximum of three starts per hour. Where designers choose not to fit buffer tanks, system zoning and zone controls should ensure that the minimum emission load available to the heat pump is closely matched to its minimum heat output.

Interruptions to steady-state operation can also be caused by a reduction in available heat emission and run-time due to flow temperature being too low due to inappropriate WCC setting, particularly with radiators. Systems were found to operate for long periods of time heating the water in the system to around 30°C before switching off, turning back on when the temperature dropped by about 5°C and a time delay had elapsed. Water circulating through the radiator system at this temperature was not hot enough to cause sufficient heat transfer into a zone which was already at 20°C and for which the target temperature was 21°C. Situations like this were found to exist for in excess of 12 hours at a time.

End users had the impression that this was acceptable because of the idea that the system is "always on" but in fact SH2.0 analysis has shown that these situations use more energy at a lower COP than the same system working at higher flow temperature which doesn't cycle, and heats the zone up to target temperature quicker before switching off. Due to the enhanced building fabric resulting from the deep retrofit process, the zone temperature can be maintained for a significant period before the compressor is called back to action.

For AHSPs, ice build-up on the evaporator was shown to be a significant issue and further work is required to determine if the energy penalty highlighted in this paper is accurately captured in current national heat pump performance tools. Sizing of heat pumps needs to take account of the defrost process as it was shown that systems that are marginally undersized can struggle to maintain house temperatures when defrosting is occurring on a regular basis.

A combination of thorough commissioning, including at least one post-commissioning follow-up visit by the installer, greater homeowner engagement and ongoing annual inspections is required to ensure that each system is fully adapted to the requirements of the building and the residents that it serves.

6. Future work

LIT is currently conducting additional research in relation to heat pumps to further inform the market and increase capacity. This research includes:

- SEAI RD&D funded project FactHP is monitoring 40 domestic heat pump (air and ground source, new-build and retrofit) systems and will compare the combined annual Seasonal Performance Factor (SPF) for heating and hot water with that predicted by DEAP to determine if an in-use factor is required. This research is due for completion at the end of 2020[1];
- Funded under the H2020 programme the HP4ALL project will develop tools and resources to increase skills across the heat pump supply chain[2]. Coordinated by LIT, this project commenced in September 2020 and will have a 30-month duration.

As the quantity and range of heat pumps which are installed within the residential sector increases, additional research and analysis is also required across the following areas:

- Impacts of heat pumps on the electrical grid;
- Integration of heat pumps with electric vehicle (EV), renewable generation systems i.e. PV and battery storage;
- Customer/homeowner knowledge and behaviour.

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